SEISMIC HARMONIZATION IN EUROPE

WP4 STRONG GROUND MOTION MODELING

A REPORT ON THE EVALUATION OF GROUND MOTION PREDICTION EQUATIONS WITHIN THE CONTEXT OF SHARE WP4 TASKS

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1. Introduction

This report evaluates a set of ground-motion prediction equations (GMPEs) from active shallow crustal regions to comply with Task 4.2 in SHARE-WP4 that aims to convey information about the performance of existing regional/global ground-motion models for characterizing the ground motion in Europe. The predictive models evaluated in this report are selected by J. Douglas and they are ranked by the criteria proposed in Scherbaum et al. (2009). The report briefs the evaluated GMPEs, describes the databases used in the evaluations, defines the theoretical background of the aforementioned ranking procedure and discusses the major outcomes after presenting the rankings for different spectral periods and peak ground motions.

2. Ground motion prediction equations evaluated

The set of GMPEs evaluated in this report are listed in Table 1.

Table 1. Candidate ground-motion models for active crustal regions.

Model	Database	M[a]	M Range	Dis.[b]	Dis. Range	Period Range	Soil Class[e]	SoF[c]	Comp.[d]
Akkar and Bommer (2010)	Europe – Middle East	M_w	5.0-7.6	R_{jb}	0-99	0.05 – 3.0s PGA, PGV	Vs30 < 360, 360 < V_{S30} < 760, and V_{S30} > 760	N, R/T, S	GM
Boore and Atkinson (2008)	Worldwide	M_w	4.2-7.9	R_{jb}	0-200	0.01-10.0s PGA, PGV	Continuous function of V_{s30}	N, R, S, U	GMRotI50
Cauzzi and Faccioli (2008)	Worldwide	M_w	5.0-7.2	R_{hyp}	6-150	0.05-20s PGA	Vs30 < 180, 180 < V_{S30} < 360, 360 < V_{S30} < 800, and V_{S30} > 800	N, R/T, S	GM
Cotton et al. (2008)	Japan	M_w	4.0-7.3	R_{rup}	5-100	0.01-3.0	Vs30 < 180, 180 < V_{S30} < 360, 360 < V_{S30} < 800,and V_{S30} > 800		GM
Zhao et al. (2006)	Japan	M_w	5.0-7.4	R_{rup}	0.4-300	0.05-5.0 PGA	Vs30 < 200, 200 < V_{S30} < 300, 300 < V_{S30} < 600, 600 < V_{S30} < 1100 and V_{S30} > 1100	N, R, S	GM
Bindi et al. (2009)	Italy	M_w	4.0-6.9	R_{jb}, R_{epi}	1-100	0.03-2.0s PGA, PGV	Vs30 < 400, 400 < V_{S30} < 800, V_{S30} > 800		LE
Danciu and Tselentis (2007)	Greece	M_w	4.5-6.9	R_{epi}	0-136	0.1-4.0 s PGA, PGV	V_{S30} < 360, 360 < V_{S30} < 800,and V_{S30} > 800	N, R/T, S	AM
Douglas et al.(2006)	Worldwide	M_w	4.5-7.5	R_{jb}	1-300	0.02-2.0s	1870 m/s		GM
Kalkan and Gülkan (2004)	Turkey	M_w	4.0-7.4	R_{jb}	1.2-250	0.1-2.0 s PGA	Continuous function of V_{S30}		LE
Massa et al. (2008)	Northern Italy	M_w	4.5-6.5	R_{epi}	1-100	0.04-2.0 s PGA	V_{S30} < 800, V_{S30} > 800		LE

[a] **M** refers to magnitude and M_w stands for moment magnitude. [b] **Dis** refers to distance metric; R_{jb} is Joyner-and Boore distance, R_{epi} is epicentral distance, R_{hyp} is hypocentral distance and R_{rup} is closest distance to rupture surface. [c] **SoF** stands for style-of-faulting; N is normal, R is reverse, T is thrust and S is strike-slip. [d] **Comp** abbreviates horizontal component of ground motion, GM is geometric mean, GMRotI50 is rotation independent median geometric mean (Boore et al., 2006), AM is arithmetic mean and LE is maximum of horizontal components, e The shear-wave velocity values represent V_{s30} in m/s.

All models are developed for moment magnitude M_w. In general, the considered GMPEs estimate ground motions between $4 < M_w < 8$. Akkar and Bommer (2010), Boore and Atkinson (2008), Douglas et al. (2006) and Kalkan and Gülkan (2004) use Joyner-Boore (R_{jb}) distance metric. The models proposed by Danciu and Tselentis (2007) and Massa et al. (2008) employ epicentral distance (R_{epi}) whereas models based on Japanese data (i.e. Zhao et al. (2006) and Cotton et al. (2008) use R_{rup} (rupture distance). Cauzzi and Faccioli (2008) use hypocentral distance (R_{hyp}). We note that Bindi et al. (2009) provides different sets of coefficients for R_{epi} and R_{jb}. As listed in Table 1, the distance ranges show significant variations between the models.

Boore and Atkinson (2008) and Kalkan and Gülkan (2004) GMPEs describe site class as a continuous function of V_{S30} whereas the rest of the models use generic site class definitions (e.g. rock, stiff, soft) that are defined for an interval of V_{S30}. Except for Kalkan and Gülkan (2004) and Massa et al. (2008), all models consider the style-of-faulting (SoF) as an estimator parameter that accounts for the differences between normal, reverse/thrust and strike-slip faults.

The majority of models use geometric mean as the horizontal component definition. Boore and Atkinson (2008) use GMRotI50 (Boore et al. 2006) as the horizontal component definition that yields, on average, similar estimations as GM (Beyer and Bommer, 2006).

Danciu and Tselentis (2007) model estimates the horizontal-component ground motions for arithmetic mean. Bindi et al. (2009), Kalkan and Gülkan (2004) and Massa et al. (2008) models estimate ground motions for the maximum of two horizontal components.

All models cover PGA and spectral ordinate estimations up to 2 - 3 seconds. Some of the models estimate spectral ordinates beyond this period range. Zhao et al. (2006) estimate ground motions for periods up to 5 seconds whereas Boore and Atkinson (2008) and Cauzzi and Faccioli (2007) reach to spectral ordinate estimations of 10 and 20 seconds, respectively. Among the evaluated models, few of them can also estimate PGV (i.e. Akkar and Bommer, 2010; Boore and Atkinson, 2008; Bindi et al. 2009 and Danciu and Tselentis, 2007).

3. Databases used in the evaluation

We used different testbed databases of SHARE strong-motion databank (Yenier et al., 2010[1]). Each GMPE is evaluated according to the horizontal-component definition implemented in the model. The only exception to this rule is the Boore and Atkinson (2008) model for which we used GM horizontal-component definition instead of GMRotI50. Our decision is based on the statistical results in Beyer and Bommer (2006) that showed, on average, no difference between GM and GMRotI50 component definitions. For GMPEs that use generic site class definitions, we considered the V_{S30} intervals proposed by the model developers to classify the soil conditions in the GMPE-specific ground-motion bins. Two main testbed databases are assembled for the evaluation of GMPEs whose main features are summarized below:

Database DB1: This testbed database consists of European strong-motion recordings from the ISESD[2], ESMD[2], and T-NSMP databanks. A total of 1376 records is gathered together from these databanks with focal depths less than 40 km. The magnitude range of DB1 is 3.0 < M_w < 7.6 and it contains records with distances up to 400 km. Each recording in DB1 is described by moment magnitude (M_w), contains the distance values of interest (R_{epi}, R_{hyp}, R_{jb} and R_{rup}), its site class is defined by V_{s30} and style-of-faulting information is available. Figures 1 and 2 describe the magnitude vs. distance (R_{jb}) distribution of the strong-motion records in DB1 as a function of site class (Figure 1) and style-of-faulting (Figure 2).

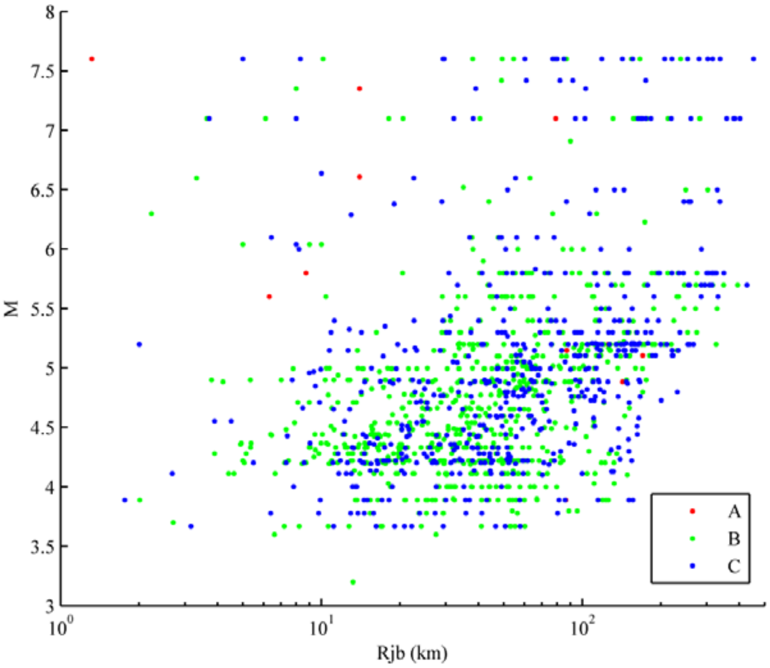

Figure 1. Magnitude (M_w) vs. distance (R_{jb}) distribution of DB1 as a function of site class. The red, yellow and blue points are rock (A), stiff (B) and soft (C) site recordings with V_{S30} > 760 m/s, 360 m/s < V_{S30} < 760 m/s and V_{S30} < 360 m/s, respectively.

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[1] SHARE strong-motion databank is gathered from many strong-motion sources (ISESD, NGA, Kik-Net, T-NSMP etc.) as discussed in Yenier et al. (2010). The duplicated records among those sources are removed in the final version of the SHARE databank by a set of criteria described in Yenier et al. (2010).

2 Although, the recently compiled Italian data (ITACA) are considered in the SHARE strong-motion databank, the pertaining recordings do not contain information about R_{rup}. Therefore, we considered the Italian strong-motion records in the ISESD and ESMD databanks since these two databanks provide information for the entire distance metrics used in this study (i.e. R_{epi}, R_{hyp}, R_{jb} and R_{rup}).

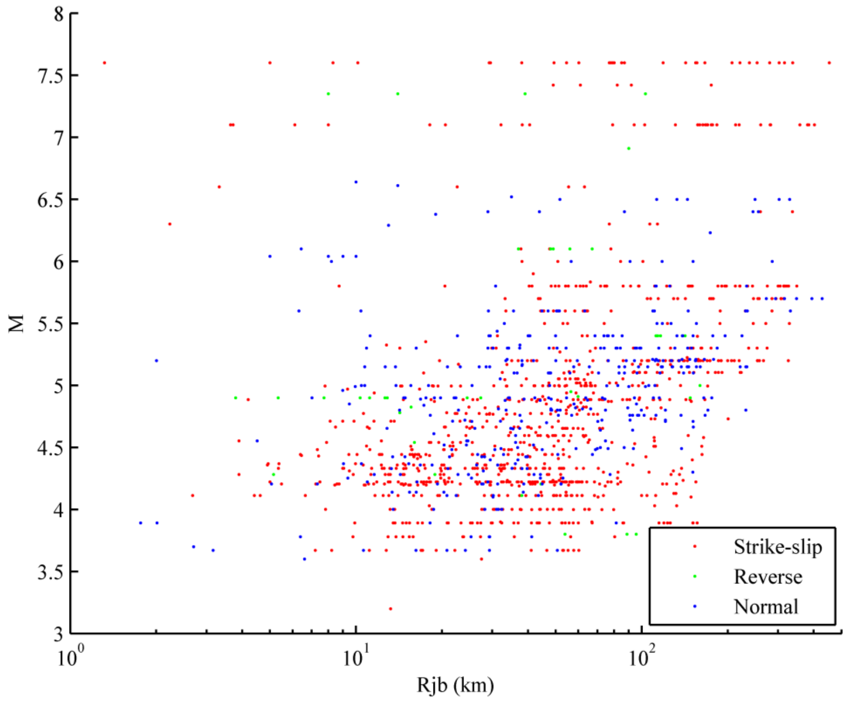

Figure 2. Magnitude (M_w) vs. distance (R_{jb}) distribution of DB1 as a function of style-of-faulting.

Database DB2: This testbed database contains recordings from NGA, KIK-net and Cauzzi and Faccioli databanks (see details in Yenier et al., 2010). A total of 1755 records with depths less than 40 km is gathered from these data sources to assemble DB2. Similar to DB1, each record is described by moment magnitude (M_w) and has all the distance (i.e. R_{epi}, R_{hyp}, R_{jb} and R_{rup}) as well as site (in terms of V_{s30}) and style-of-faulting information. Its major difference with respect to DB1 is the magnitude range that is between $5.5 < M_w < 7.9$. Figures 3 and 4 describe the magnitude vs. distance (R_{jb}) distribution of DB2 as a function of site class (Figure 3) and style-of-faulting (Figure 4).

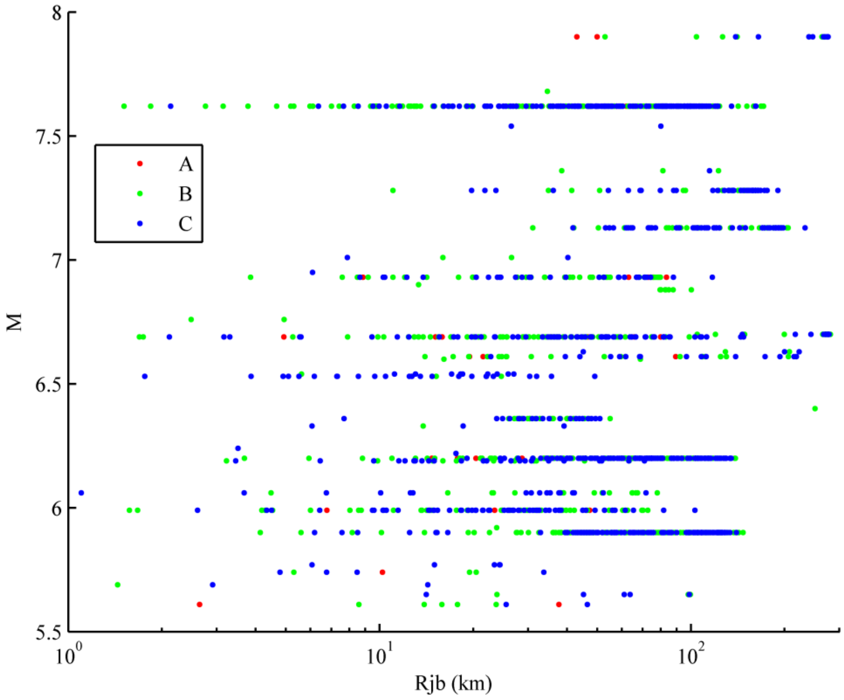

Figure 3. Magnitude (M_w) vs. distance (R_{jb}) distribution of DB2 in terms of different site classes. The red, yellow and blue points are rock (A), stiff (B) and soft (C) site records with V_{S30} > 760 m/s, 360 m/s < V_{S30} < 760 m/s and V_{S30} < 360 m/s, respectively.

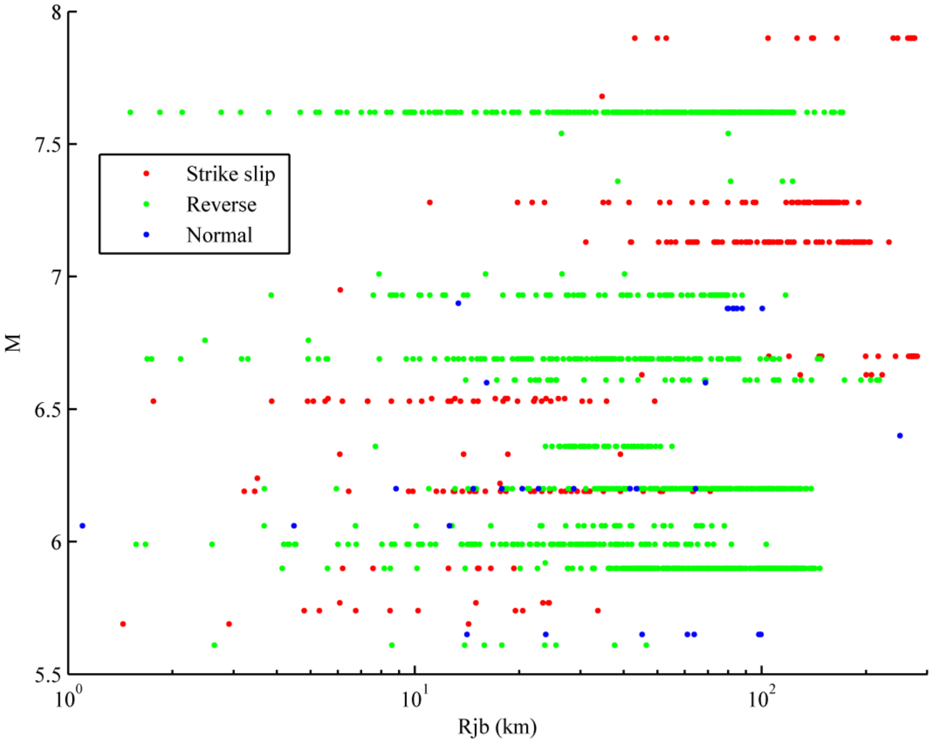

Figure 4. Magnitude (M_w) vs. distance (R_{jb}) distribution of DB2 in terms of style-of-faulting.

DB1 and DB2 can serve for two main purposes:

i) Evaluating the performance of candidate GMPEs by using the ground motions from Europe and surrounding regions (DB1 specifically serves for this purpose).

ii) Evaluating the performance of candidate GMPEs by using the ground motions from other parts of the world with larger magnitudes (DB2 specifically serves for this purpose). We note that European strong-motion records in DB1 were excluded from DB2

Rock recordings of DB1 and DB2 with V_{s30} > 760m/s are grouped as separate datasets to perform additional evaluations on candidate GMPEs since WP4 is primarily focused on the estimation of rock ground motions. A total of 11 accelerograms from DB1 and 47 accelerograms from DB2 are qualified as rock recordings (i.e. V_{s30} > 760m/s) and these subsets are designated as $DB1_{(rock)}$ and $DB2_{(rock)}$ in this report.

We also ran additional evaluations on the candidate GMPEs to calculate their ranking for large magnitude events (i.e. $M_w > 6.5$). For this purpose, we assembled two other ground-motion bins from DB1 and DB2 with $M_w > 6.5$. These bins are referred to as $DB1_M$ (contains a total of 82 records from DB1) and $DB2_M$ (contains a total of 933 records from DB2) in this report. Table 2 lists the site class-dependent record distribution in DB1, DB2, $DB1_{(M)}$ and $DB2_{(M)}$.

Table 2. Number of records in DB1, DB2, $DB1_{(M)}$ and $DB2_{(M)}$ for different site classes

Site Class	Databases			
	DB1	DB2	$DB1_{(M)}$	$DB2_{(M)}$
Rock (V_{S30} > 760 m/s)	11	47	4	29
Stiff (360 m/s < V_{S30} < 760 m/s)	791	832	29	424
Soft (V_{S30} < 360 m/s)	572	876	49	480

As the final task of this report, we evaluated the candidate GMPEs for near-fault records with R_{jb} distances less than 20 km and $M_w > 6.5$. In order to achieve this purpose we assembled a sub bin from DB2 with a total of 159 recordings that is referred to as $DB2_{NF}$.

4. Evaluation methodology

4.1. Ranking Criteria

Ranking of GMPEs follow the recent method proposed in Scherbaum et al. (2009) (LLH method) since its predecessor (i.e. LH method; Scherbaum et al., 2004) is sensitive to data size (Delavoud et al., 2009) and it might become biased for GMPE rankings done by using small number of data.

The method is based on the estimation of the distance between two models defined as distributions. GMPEs are ranked according to a criterion noted in LLH which gives the log likelihood of a model given a set of data (i.e. how likely a model has generated the data). LLH is defined as the negative average log-likelihood of the model g given the sample set x of N observations:

$$LLH = -\frac{1}{N}\sum_{i=1}^{N}\log_2\left(g\left(x_i\right)\right)$$

This report provides the ranking of candidate GMPEs through their LLH values that can be used as supplementary information in calculating the weights for their implementation to PSHA.

4.2. Implementation Comments

Before presenting the ranking of the models we note the following comments during the application of LLH:

- The ground-motion estimations of Boore and Atkinson (2008) are calculated by a FORTRAN executable code provided by the first author. This model estimates for GMRotI50. As stated previously, we assumed the equality of GMRotI50 and GM since we did not calculate GMRotI50 of the horizontal components of the observed data.
- For Cauzzi and Faccioli (2008) model, we used Eqs. (8) and (2) from the same paper for predicting peak ground acceleration and spectral displacement values, respectively.
- We used the R_{jb}-based Bindi et al. (2009) model (side note: Bindi et al. (2009) derives two sets of regression coefficients for estimating ground motions in terms of R_{epi} and R_{jb}). To this end, for small magnitude recordings (i.e. $M_w < 5.5$) with unknown R_{jb} in the observed data, we used R_{epi} instead of R_{jb} by making use of the point source assumption.
- Ground-motion estimations of Douglas et al. (2006) model are the averages of seven models, mostly derived from the WUS strong-motion data, with regional adjustments for their application in Southern Spain. The standard deviation of Douglas et al. (2006) model is

$$\sigma = \sqrt{\left(\overline{\sigma}\right)^2 + \sigma^2{}_{model}}$$

where $\overline{\sigma}$ is the average standard deviation of the seven adjusted models and σ_{model} is the standard deviation calculated from the residuals between the predicted values, of the model adjusted for Southern Spain, and the predicted values of each of the seven adjusted models.

- While evaluating the Zhao et al. (2006) model we included the magnitude square correction term per suggestions of the proponents for shallow crustal events.
- LLH criterion is derived at periods T = 0.0s (PGA), 0.1 s, 0.15 s, 0.2 s, 0.3 s, 0.5 s, 1 s and 2 s. In the evaluation of Cotton et al. (2008) we used their ground-motion estimations at T=0.096993s, 0.147059 s, 0.203666 s, 0.308642 s, 0.469484 s, 0.943396 s and 1.960784 s that are the closest periods to the chosen periods in this report.
- Before running LLH for the entire GMPEs, we made cross checks with the Polimi, LGIT and GFZ groups who apply the same type of ranking methodology to the other ground-motion models. Our cross checks based on the same sample data and using the same model resulted in the same LH and LLH values.

5. Rankings based on the LLH method

LLH method is implemented to the models presented in Section 2 by using the two main databases DB1 and DB2 as well as their subsets $DB1_{(rock)}$, $DB2_{(rock)}$, $DB1_M$, $DB2_M$ and $DB2_{NF}$. The appendix of this report shows the GMPE rankings using median LLH-values first for PGA followed by the pseudo spectral acceleration ordinates at T = 0.1 s, 0.15 s, 0.2 s, 0.3 s, 0.5 s, 1 s and 2 s.

In order to give a general view for LLH rankings, Tables 3-9 list the average LLH-values over the 5 period estimators (i.e. T = 0.1s, 0.2s, 0.5s, 1.0s and 2.0s) for DB1 and DB2 as well as for their subsets. A similar approach is also followed in Delavaud et al. (2009) for the GMPEs evaluated in their paper.

Table 3. Ranking of GMPEs by the average sample log-likelihood criterion averaged over 5 period estimators (DB1).

Rank	LLH	Model
1	2.2781	Cotton et al. (2008)
2	2.4484	Bindi et al. (2009)
3	2.4521	Cauzzi and Faccioli (2008)
4	2.5924	Douglas et al. (2006)
5	2.6473	Akkar and Bommer (2010)
6	2.8672	Zhao et al. (2006)
7	3.4585	Danciu and Tselentis (2007)
8	4.2572	Boore and Atkinson (2008)
9	5.1193	Kalkan and Gülkan (2004)
10	5.7095	Massa et al. (2008)

Table 4. Ranking of GMPEs by the average sample log-likelihood criterion averaged over 5 period estimators (DB2).

Rank	LLH	Model
1	1.5585	Akkar and Bommer (2010)
2	1.6112	Boore and Atkinson (2008)
3	1.6745	Kalkan and Gülkan (2004)
4	1.7675	Bindi et al. (2009)
5	1.8177	Danciu and Tselentis (2007)
6	1.8410	Cauzzi and Faccioli (2008)
7	1.8447	Zhao et al. (2006)
8	2.0142	Cotton et al. (2008)
9	2.5471	Douglas et al. (2006)
10	3.3221	Massa et al. (2008)

Table 5. Ranking of GMPEs by the average sample log-likelihood criterion averaged over 5 period estimators (DB1$_{(rock)}$).

Rank	**LLH**	**Model**
1	1.7295	Bindi et al. (2009)
2	2.0620	Akkar and Bommer (2010)
3	2.1186	Douglas et al. (2006)
4	2.2225	Cotton et al. (2008)
5	2.2531	Cauzzi and Faccioli (2008)
6	2.6111	Zhao et al. (2006)
7	3.7193	Boore and Atkinson (2008)
8	4.9288	Danciu and Tselentis (2007)
9	5.4041	Kalkan and Gülkan (2004)
10	6.5974	Massa et al. (2008)

Table 6. Ranking of GMPEs by the average sample log-likelihood criterion averaged over 5 period estimators (DB2$_{(rock)}$).

Rank	**LLH**	**Model**
1	1.4756	Akkar and Bommer (2010)
2	1.5298	Boore and Atkinson (2008)
3	1.5616	Zhao et al. (2006)
4	1.6547	Kalkan and Gülkan (2004)
5	1.6808	Danciu and Tselentis (2007)
6	1.6866	Bindi et al. (2009)
7	1.7862	Douglas et al. (2006)
8	1.8084	Cauzzi and Faccioli (2008)
9	1.9001	Cotton et al. (2008)
10	3.3051	Massa et al. (2008)

Tables 3 to 6 suggest that, except for DB1, Akkar and Bommer (2010) model rank relatively better with respect to the other candidate GMPEs for all site conditions (i.e. DB1, DB2) and for rock sites (i.e. DB1$_{(rock)}$ and DB2$_{(rock)}$). The relatively lower performance of Akkar and Bommer (2010) in DB1 can, speculatively, be attributed to the low magnitude bound ($M_w \approx 3.5$) of this database. Bindi et al. (2009), Douglas et al. (2006), and Cotton et al. (2008) draw consistently better performance (always on the upper half of the list) for DB1 and DB1$_{(rock)}$ that constitute recordings from the European data sources. In a similar manner, Boore and Atkinson (2008), Kalkan and Gülkan (2004) and Danciu and Tselentis (2007) generally behave well for DB2 and DB2$_{(rock)}$ datasets that are assembled from recordings outside of Europe. We note that of these models Kalkan and Gülkan (2004), Danciu and Tselentis (2007) and Cotton et al. (2008) are derived from country-specific ground-motion datasets and they perform better for the databases assembled from ground motions recorded outside these countries. The controversial case to this observation is the Bindi et al. (2009) model that performs relatively better within the datasets assembled from European recordings. This might be attributed to the data scatter (data distribution in terms of magnitude and distance) of the testbed databases. Confined to the testbed datasets that mainly put emphasis on the site class feature for a broader magnitude and distance interval (i.e. DB1, DB2, DB1$_{(rock)}$ and DB2$_{(rock)}$), we could not make clear-cut observations about the performance differences among the GMPEs derived either from country-specific or more general datasets. The only consistent ranking is observed for the Massa et al. (2008) model that is derived from a very local (north of Italy) set of ground motions. This model yields the lowest performance in terms of in terms of ranking for all the databases used in this study.

Table 7. Ranking of GMPEs by the average sample log-likelihood criterion averaged over 5 period estimators ($DB1_M$).

Rank	**LLH**	**Model**
1	1.8126	Boore and Atkinson (2008)
2	1.8906	Zhao et al. (2006)
3	1.9927	Cauzzi and Faccioli (2008)
4	2.2752	Akkar and Bommer (2010)
5	2.2982	Cotton et al. (2008)
6	2.3104	Kalkan and Gülkan (2004)
7	2.5419	Bindi et al. (2009)
8	2.6898	Douglas et al. (2006)
9	2.9050	Danciu and Tselentis (2007)
10	4.1042	Massa et al. (2008)

Table 8. Ranking of GMPEs by the average sample log-likelihood criterion averaged over 5 period estimators ($DB2_M$).

Rank	**LLH**	**Model**
1	1.3898	Boore and Atkinson (2008)
2	1.4883	Akkar and Bommer (2010)
3	1.6586	Bindi et al. (2009)
4	1.7595	Cauzzi and Faccioli (2008)
5	1.8584	Danciu and Tselentis (2007)
6	1.9402	Zhao et al. (2006)
7	1.9507	Cotton et al. (2008)
8	2.3104	Kalkan and Gülkan (2004)
9	2.6473	Douglas et al. (2006)
10	3.3331	Massa et al. (2008)

Tables 7 and 8 indicate that regardless of the origin of the databases assembled for large magnitude events (i.e. $DB1_M$ and $DB2_M$) Boore and Atkinson (2008), Akkar and Bommer (2010) and Cauzzi and Faccioli (2008) rank relatively better with respect to the other models. This observation may suggest that models that are based on global datasets perform better for the estimation of larger magnitude events. For $DB1_M$ and $DB2_M$, the models derived from country-specific datasets generally draw poor performances except for the Zhao et al. (2006) and Bindi et al. (2009) models that hold positions on the upper half of the list for $DB1_M$ and $DB2_M$, respectively. Interestingly, Bindi et al. (2009) that is derived from the dataset specific to Italy (one of the most seismic prone countries in Europe) holds a better ranking in $DB2_M$. The opposite observation is valid for the Zhao et al. (2006) model that brings forward our speculative comment (previous paragraph) made on the influence of dataset distribution on the GMPE performance.

Table 9. Ranking of GMPEs by the average sample log-likelihood criterion averaged over 5 period estimators ($DB2_{NF}$).

Rank	LLH	Model
1	1.2626	Boore and Atkinson (2008)
2	1.3496	Akkar and Bommer (2010)
3	1.4842	Kalkan and Gülkan (2004)
4	1.6245	Bindi et al. (2009)
5	1.6609	Cotton et al. (2008)
6	1.7280	Danciu and Tselentis (2007)
7	1.7604	Cauzzi and Faccioli (2008)
8	1.7608	Douglas et al. (2006)
9	1.8819	Zhao et al. (2006)
10	3.8456	Massa et al. (2008)

Table 9 lists the average LLH-values over the spectral period range of concern for the near-fault data ($DB2_{NF}$). Boore and Atkinson (2008) and Akkar and Bommer (2010) models that are derived from global datasets take the first 2 places in ranking. These models are followed by Kalkan and Gülkan (2004) and Bindi et al. (2009) GMPEs that are derived from country-specific datasets.

Figures 6 to 11 summarize and compare the rankings of candidate GMPEs using the median LLH-values that are also presented in the appendix of this report. The ranking comparisons are presented as a function period that yields more insight about the performance of each considered model. (Note: PGA rankings are presented at T = 0.01s in all plots for the sake of simplicity). The ranking plots presented in these figures strengthen our overall remarks made from the average LLH-values listed in Tables 3 to 9. Figures 5 and 6 compare the rankings of candidate GMPEs for DB1 and DB2, respectively. Figures 7 and 8 make similar comparisons for $DB1_{(rock)}$ and $DB2_{(rock)}$, respectively whereas Figures 9 and 10 show the comparative plots derived from $DB1_{M}$ and $DB2_{M}$ The last figure (Figure 11) is prepared for the period-dependent ranking based on $DB2_{NF}$. The ranking plots in Figure 5 indicate that Cotton et al. (2008) shows a good performance for DB1 that is followed by Akkar and Bommer (2009) (improves for T > 0.2s), Bindi et al. (2009) (yields good ranking except for T = 2.0s) and Cauzzi and Faccioli (2008) (much better performance at shorter periods). The Douglas et al. (2006) model gives a stable trend with a moderate ranking whereas the other candidate GMPEs do not yield satisfactory ranking. Figure 6 that summarizes the period-dependent ranking for DB2 describes better performances for Akkar and Bommer (2010) and Boore and Atkinson (2008). These models are followed by Bindi et al. (2009) and Cauzzi and Faccioli (2008) that tend to perform better at shorter periods. Our comments envisaged from the trends in Figures 5 and 6 do not change significantly for the rankings presented in Figures 7 and 8 that constitute the model evaluations using only the rock site recordings of DB1 and DB2, respectively. Figures 9 and 10 illustrate the superior performance of Akkar and Bommer (2010), Boore and Atkinson (2008) and Cauzzi and Faccioli (2008) with respect to other models when the datasets are assembled from large magnitude datasets regardless of the data origin (i.e. either within or outside of Europe). As noted previously the better performing models are derived from datasets that constitute ground motions recorded at different countries of similar tectonics. However, this consistent behavior is only limited to the testbed databases with large magnitude (M_w > 6.5) events. The near-fault related ranking (Figure 11) shows Boore and Atkinson (2008) and Akkar and Bommer (2010) as the most successful models throughout the period range of interest.

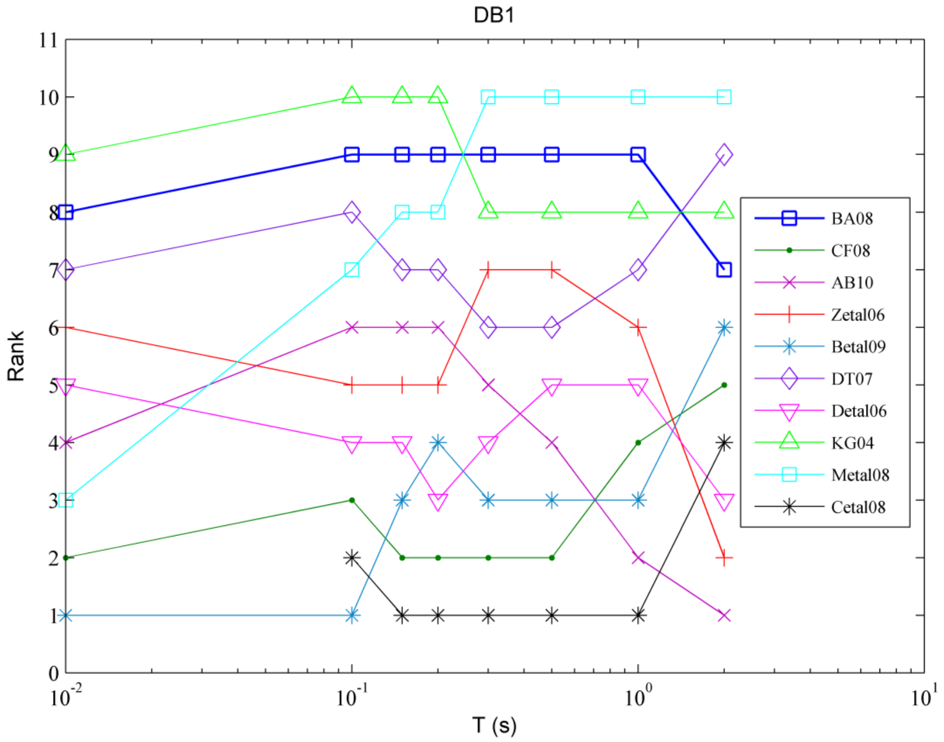

Figure 5. Comparative rankings of candidate GMPEs as a function of period using DB1 from median LLH-values

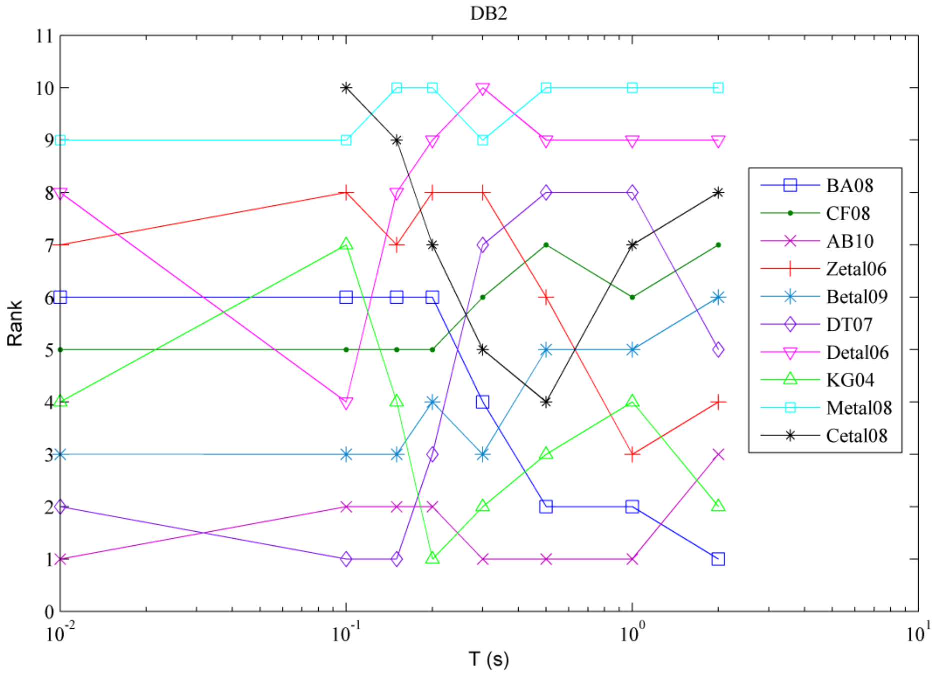

Figure 6. Comparative rankings of candidate GMPEs as a function of period using DB2 from median LLH-values

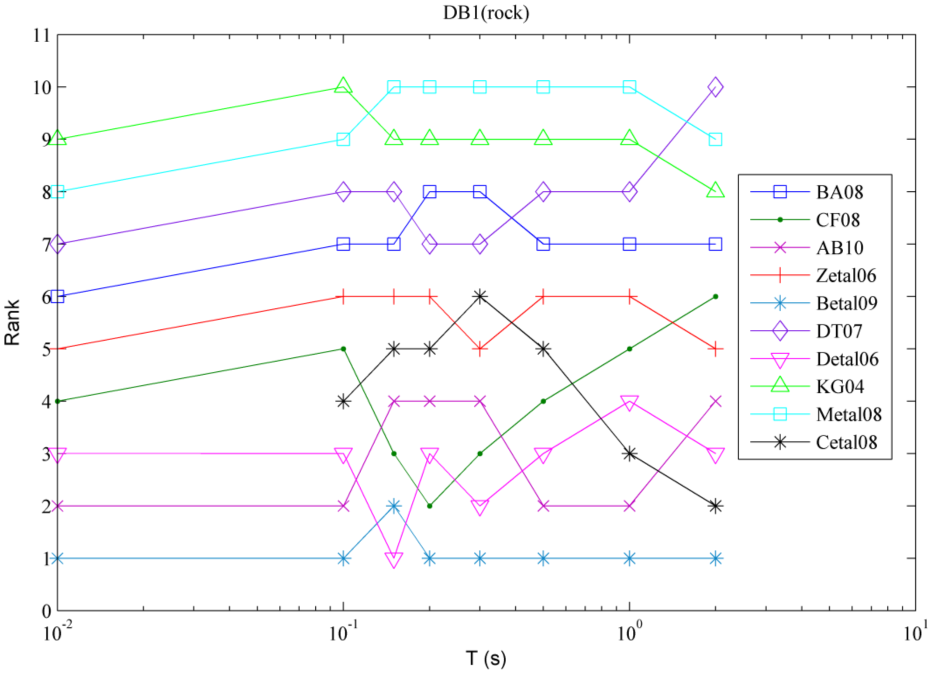

Figure 7. Comparative rankings of candidate GMPEs as a function of period using $DB1_{(rock)}$ from median LLH-values

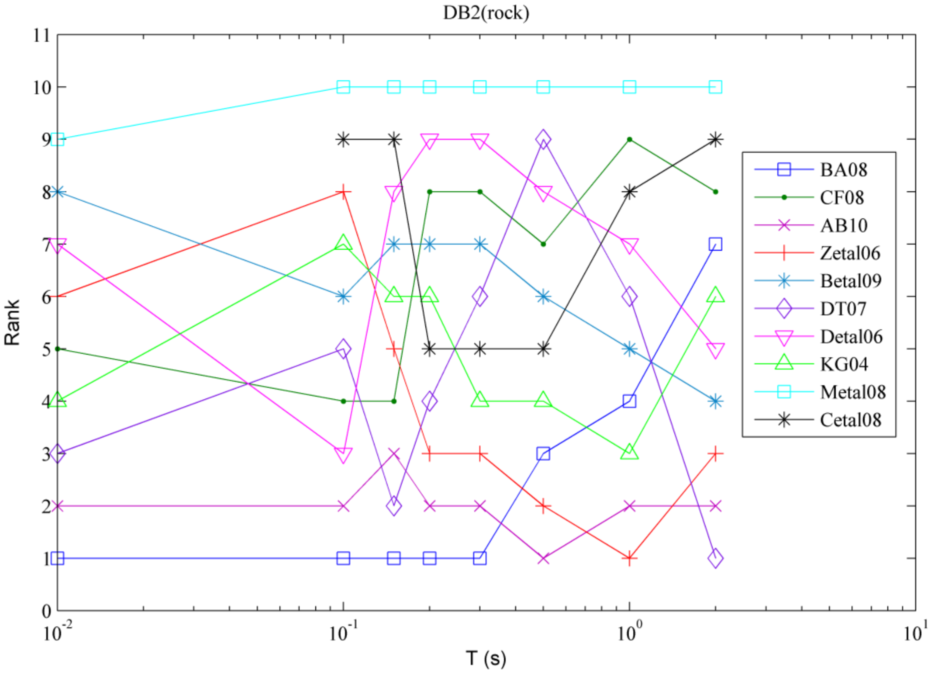

Figure 8. Comparative rankings of candidate GMPEs as a function of period using $DB2_{(rock)}$ from median LLH-values

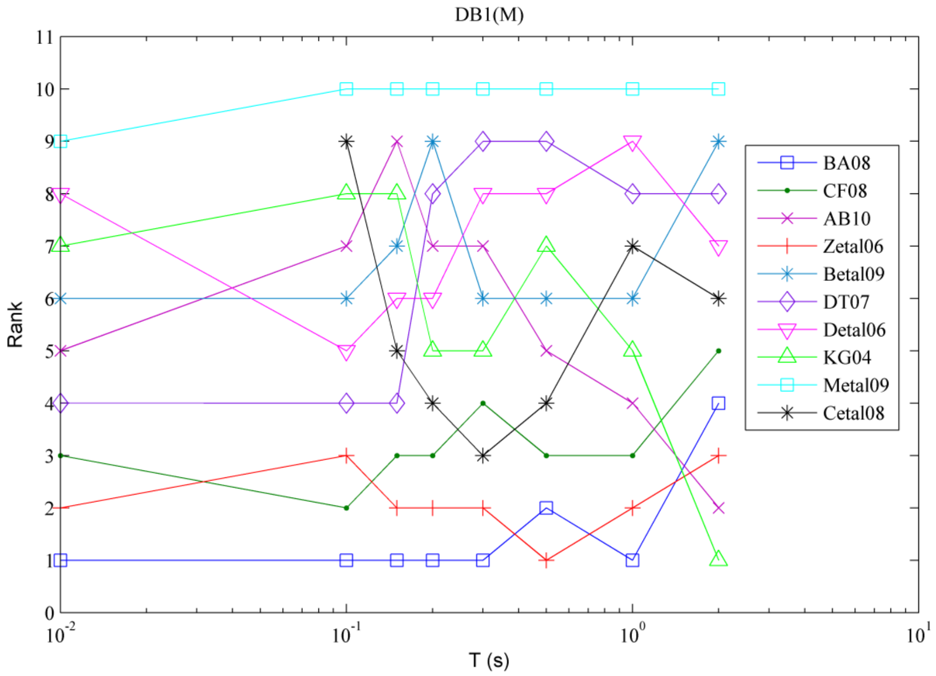

Figure 9. Comparative rankings of candidate GMPEs as a function of period using $DB1_{(M)}$ from median LLH-values

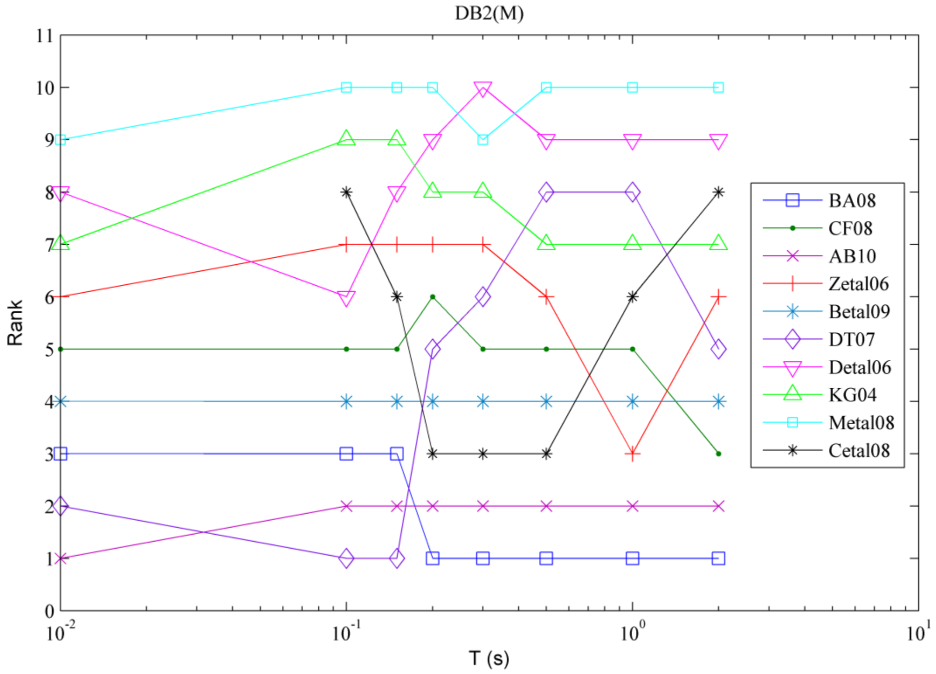

Figure 10. Comparative rankings of candidate GMPEs as a function of period using $DB2_{(M)}$ from median LLH-values

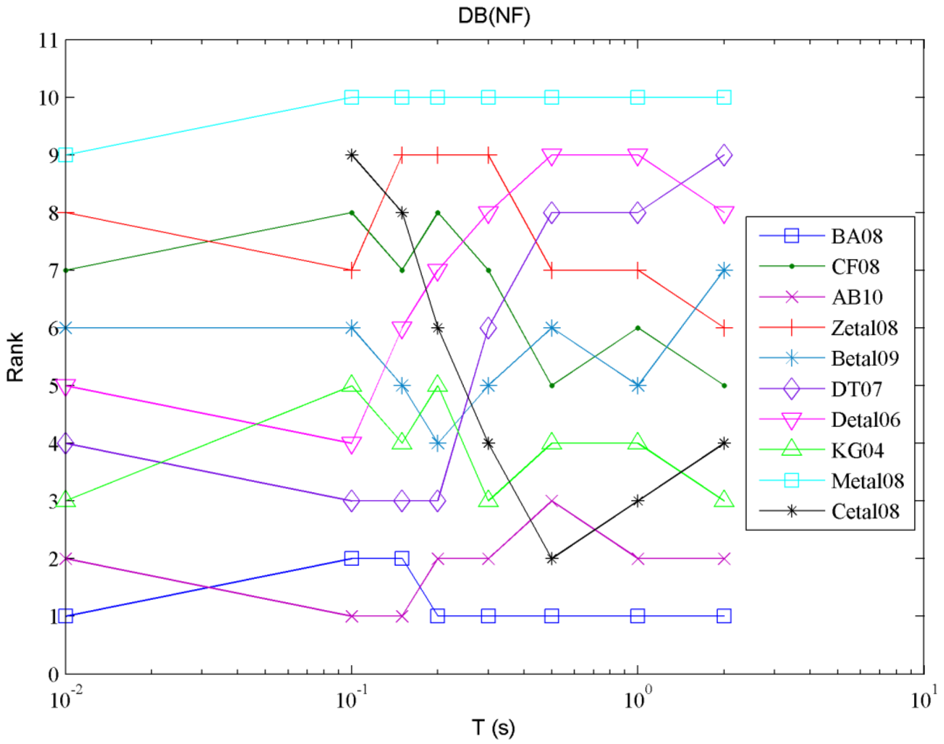

Figure 11. Comparative rankings of candidate GMPEs as a function of period using $DB2_{(NF)}$ from median LLH-values

6. Summary and Conclusions

We evaluated the pre-selected candidate GMPEs to characterize the ground motion in Europe. This work is done to comply with Task 4.2 in SHARE-WP4. The datasets for ranking are assembled from the SHARE strong-motion databank and they consist of recordings (a) from Europe and surrounding regions (DB1) and (b) from other shallow-crustal active regions of the globe (DB2). We also gathered sub-bins from these two major datasets to see the performance of candidate GMPEs for rock site recordings ($DB1_{(rock)}$, $DB2_{(rock)}$), for large magnitude events ($DB1_M$, $DB2_M$) and for near-fault records ($DB2_{NF}$). The implemented ranking methodology is proposed in Scherbaum et al. (2009) (LLH-method) that is independent of the size of the ground-motion dataset. We made the following observations from the evaluations of candidate GMPEs:

- There is no clear dominance of global models over country-specific GMPEs for datasets that bring forward the site class for a broad range of magnitude and distance interval (i.e. DB1, DB2, $DB1_{(rock)}$ and $DB2_{(rock)}$). For such datasets our evaluations showed better rankings for Akkar and Bommer (2010), Boore and Atkinson (2008), and Bindi et al. (2009).
- Global predictive models (Akkar and Bommer, 2010; Boore and Atkinson, 2008; Cauzzi and Faccioli, 2008) seem to do better for large magnitude events ($DB1_M$ and $DB2_M$).
- Confined to the near-fault dataset used, the ranking of Akkar and Bommer (2010) and Boore and Atkinson (2008) models supersedes the other GMPEs.

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Appendix– Ranking of Predictive Models According to LLH (Scherbaum et al., 2009)

A. DB1 database:

Table 10. Ranking of GMPEs for peak ground acceleration (DB1)

Rank	LLH	Model
1	2.3760	Bindi et al. (2009)
2	2.4107	Cauzzi and Faccioli (2008)
3	2.7675	Massa et al. (2008)
4	2.9194	Akkar and Bommer (2010)
5	3.0032	Douglas et al. (2006)
6	3.1279	Zhao et al. (2006)
7	3.6340	Danciu and Tselentis (2007)
8	4.8652	Boore and Atkinson (2008)
9	6.5547	Kalkan and Gülkan (2004)

Table 11. Ranking of GMPEs for PSA at T=0.1 sec (DB1)

Rank	LLH	Model
1	2.4888	Bindi et al. (2009)
2	2.5001	Cotton et al. (2008)
3	2.7350	Cauzzi and Faccioli (2008)
4	2.8934	Douglas et al. (2006)
5	2.9158	Zhao et al. (2006)
6	2.9495	Akkar and Bommer (2010)
7	3.7695	Massa et al. (2008)
8	3.8321	Danciu and Tselentis (2007)
9	4.5879	Boore and Atkinson (2008)
10	7.5143	Kalkan and Gülkan (2004)

Table 12. Ranking of GMPEs for PSA at T=0.15 sec (DB1)

Rank	LLH	Model
1	2.2836	Cotton et al. (2008)
2	2.4471	Cauzzi and Faccioli (2008)
3	2.4925	Bindi et al. (2009)
4	2.5187	Douglas et al. (2006)
5	2.8577	Zhao et al. (2006)
6	3.1423	Akkar and Bommer (2010)
7	3.5038	Danciu and Tselentis (2007)
8	4.0943	Massa et al. (2008)
9	4.6969	Boore and Atkinson (2008)
10	6.1562	Kalkan and Gülkan (2004)

Table 13. Ranking of GMPEs for PSA at T=0.20 sec (DB1)

Rank	LLH	Model
1	2.2407	Cotton et al. (2008)
2	2.3329	Cauzzi and Faccioli (2008)
3	2.4618	Douglas et al. (2006)
4	2.4715	Bindi et al. (2009)
5	3.0059	Zhao et al. (2006)
6	3.1849	Akkar and Bommer (2010)
7	3.5678	Danciu and Tselentis (2007)
8	4.4729	Massa et al. (2008)
9	4.5964	Boore and Atkinson (2008)
10	5.2787	Kalkan and Gülkan (2004)

Table 14. Ranking of GMPEs for PSA at T=0.30 sec (DB1)

Rank	LLH	Model
1	2.2609	Cotton et al. (2008)
2	2.3215	Cauzzi and Faccioli (2008)
3	2.4324	Bindi et al. (2009)
4	2.5474	Douglas et al. (2006)
5	2.9838	Akkar and Bommer (2010)
6	3.0655	Bindi et al. (2009)
7	3.3270	Zhao et al. (2006)
8	4.4183	Kalkan and Gülkan (2004)
9	4.5725	Boore and Atkinson (2008)
10	4.8687	Massa et al. (2008)

Table 15. Ranking of GMPEs for PSA at T=0.50 sec (DB1)

Rank	LLH	Model
1	2,1949	Cotton et al. (2008)
2	2,3524	Cauzzi and Faccioli (2008)
3	2,3721	Bindi et al. (2009)
4	2,5900	Akkar and Bommer (2010)
5	2,6227	Douglas et al. (2006)
6	3,0407	Danciu and Tselentis (2007)
7	3,3741	Zhao et al. (2006)
8	4,9305	Kalkan and Gülkan (2004)
9	5,0451	Boore and Atkinson (2008)
10	5,5242	Massa et al. (2008)

Table 16. Ranking of GMPEs for PSA at T=1.00 sec (DB1)

Rank	LLH	Model
1	2.1057	Cotton et al. (2008)
2	2.3833	Akkar and Bommer (2010)
3	2.3975	Bindi et al. (2009)
4	2.4801	Cauzzi and Faccioli (2008)
5	2.6453	Douglas et al. (2006)
6	2.7823	Zhao et al. (2006)
7	2.9325	Danciu and Tselentis (2007)
8	4.1755	Kalkan and Gülkan (2004)
9	4.2127	Boore and Atkinson (2008)
10	7.2375	Massa et al. (2008)

Table 17. Ranking of GMPEs for PSA at T=2.00 sec (DB1)

Rank	LLH	Model
1	2.1291	Akkar and Bommer (2010)
2	2.2579	Zhao et al. (2006)
3	2.3389	Douglas et al. (2006)
4	2.3489	Cotton et al. (2008)
5	2.3598	Cauzzi and Faccioli (2008)
6	2.5122	Bindi et al. (2009)
7	2.8441	Boore and Atkinson (2008)
8	3.6974	Kalkan and Gülkan (2004)
9	3.9191	Danciu and Tselentis (2007)
10	7.5433	Massa et al. (2008)

B. DB2 database:

Table 18. Ranking of GMPEs for peak ground acceleration (DB2)

Rank	LLH	Model
1	1.4033	Akkar and Bommer (2010)
2	1.4336	Danciu and Tselentis (2007)
3	1.5244	Bindi et al. (2009)
4	1.5511	Kalkan and Gülkan (2004)
5	1.6203	Cauzzi and Faccioli (2008)
6	1.6744	Boore and Atkinson (2008)
7	1.7874	Zhao et al. (2006)
8	2.0799	Douglas et al. (2006)
9	2.6142	Massa et al. (2008)

Table 19. Ranking of GMPEs for PSA at T=0.1 sec (DB2)

Rank	LLH	Model
1	1.5887	Danciu and Tselentis (2007)
2	1.6334	Akkar and Bommer (2010)
3	1.7065	Bindi et al. (2009)
4	1.8467	Douglas et al. (2006)
5	1.8916	Cauzzi and Faccioli (2008)
6	1.8946	Boore and Atkinson (2008)
7	1.9897	Kalkan and Gülkan (2004)
8	2.1306	Zhao et al. (2006)
9	2.4722	Massa et al. (2008)
10	2.5436	Cotton et al. (2008)

Table 20. Ranking of GMPEs for PSA at T=0.15 sec (DB2)

Rank	LLH	Model
1	1.5385	Danciu and Tselentis (2007)
2	1.6522	Akkar and Bommer (2010)
3	1.6999	Bindi et al. (2009)
4	1.7068	Kalkan and Gülkan (2004)
5	1.8230	Cauzzi and Faccioli (2008)
6	1.8799	Boore and Atkinson (2008)
7	2.1078	Zhao et al. (2006)
8	2.1720	Douglas et al. (2006)
9	2.2154	Cotton et al. (2008)
10	2.6720	Massa et al. (2008)

Table 21. Ranking of GMPEs for PSA at T=0.20 sec (DB2)

Rank	LLH	Model
1	1.5810	Kalkan and Gülkan (2004)
2	1.6156	Akkar and Bommer (2010)
3	1.6259	Danciu and Tselentis (2007)
4	1.6700	Bindi et al. (2009)
5	1.7600	Cauzzi and Faccioli (2008)
6	1.7714	Boore and Atkinson (2008)
7	1.8581	Cotton et al. (2008)
8	2.0358	Zhao et al. (2006)
9	2.3938	Douglas et al. (2006)
10	2.7447	Massa et al. (2008)

Table 22. Ranking of GMPEs for PSA at T=0.30 sec (DB2)

Rank	LLH	Model
1	1.5101	Akkar and Bommer (2010)
2	1.5141	Kalkan and Gülkan (2004)
3	1.6066	Bindi et al. (2009)
4	1.6276	Boore and Atkinson (2008)
5	1.6497	Cotton et al. (2008)
6	1.6885	Cauzzi and Faccioli (2008)
7	1.7155	Danciu and Tselentis (2007)
8	1.8515	Zhao et al. (2006)
9	2.7579	Massa et al. (2008)
10	2.8311	Douglas et al. (2006)

Table 23. Ranking of GMPEs for PSA at T=0.50 sec (DB2)

Rank	LLH	Model
1	1.4589	Akkar and Bommer (2010)
2	1.4840	Boore and Atkinson (2008)
3	1.5534	Kalkan and Gülkan (2004)
4	1.5911	Cotton et al. (2008)
5	1.6812	Bindi et al. (2009)
6	1.7052	Zhao et al. (2006)
7	1.7192	Cauzzi and Faccioli (2008)
8	2.0604	Danciu and Tselentis (2007)
9	3.0413	Douglas et al. (2006)
10	3.2947	Massa et al. (2008)

Table 24. Ranking of GMPEs for PSA at T=1.00 sec (DB2)

Rank	LLH	Model
1	1.4957	Akkar and Bommer (2010)
2	1.4958	Boore and Atkinson (2008)
3	1.6266	Zhao et al. (2006)
4	1.6609	Kalkan and Gülkan (2004)
5	1.8261	Bindi et al. (2009)
6	1.8386	Cauzzi and Faccioli (2008)
7	1.8593	Cotton et al. (2008)
8	1.8716	Danciu and Tselentis (2007)
9	2.8747	Douglas et al. (2006)
10	3.8871	Massa et al. (2008)

Table 25. Ranking of GMPEs for PSA at T=2.00 sec (DB2)

Rank	LLH	Model
1	1.4102	Boore and Atkinson (2008)
2	1.5875	Kalkan and Gülkan (2004)
3	1.5888	Akkar and Bommer (2010)
4	1.7255	Zhao et al. (2006)
5	1.9421	Danciu and Tselentis (2007)
6	1.9536	Bindi et al. (2009)
7	1.9959	Cauzzi and Faccioli (2008)
8	2.2191	Cotton et al. (2008)
9	2.5792	Douglas et al. (2006)
10	4.2119	Massa et al. (2008)

C. DB1$_{(rock)}$ database:

Table 26. Ranking of GMPEs for peak ground acceleration (DB1$_{(rock)}$)

Rank	LLH	Model
1	1.6874	Bindi et al. (2009)
2	1.8627	Akkar and Bommer (2010)
3	2.0821	Douglas et al. (2006)
4	2.1019	Cauzzi and Faccioli (2008)
5	2.8018	Zhao et al. (2006)
6	3.3706	Boore and Atkinson (2008)
7	4.0768	Danciu and Tselentis (2007)
8	4.9650	Massa et al. (2008)
9	6.7133	Kalkan and Gülkan (2004)

Table 27. Ranking of GMPEs for PSA at T=0.1 sec (DB1$_{(rock)}$)

Rank	LLH	Model
1	1.7281	Bindi et al. (2009)
2	1.9709	Akkar and Bommer (2010)
3	2.1494	Douglas et al. (2006)
4	2.1704	Cotton et al. (2008)
5	2.2587	Cauzzi and Faccioli (2008)
6	2.6647	Zhao et al. (2006)
7	3.3539	Boore and Atkinson (2008)
8	3.8643	Danciu and Tselentis (2007)
9	5.5836	Massa et al. (2008)
10	7.0320	Kalkan and Gülkan (2004)

Table 28. Ranking of GMPEs for PSA at T=0.15 sec (DB1$_{(rock)}$)

Rank	LLH	Model
1	1.6756	Douglas et al. (2006)
2	1.8317	Bindi et al. (2009)
3	1.8703	Cauzzi and Faccioli (2008)
4	1.9012	Akkar and Bommer (2010)
5	2.0857	Cotton et al. (2008)
6	2.1464	Zhao et al. (2006)
7	2.7586	Boore and Atkinson (2008)
8	3.0532	Danciu and Tselentis (2007)
9	4.7904	Kalkan and Gülkan (2004)
10	5.5719	Massa et al. (2008)

Table 29. Ranking of GMPEs for PSA at T=0.20 sec (DB1$_{(rock)}$)

Rank	LLH	Model
1	1.9367	Bindi et al. (2009)
2	2.0588	Cauzzi and Faccioli (2008)
3	2.1224	Douglas et al. (2006)
4	2.1960	Akkar and Bommer (2010)
5	2.2310	Cotton et al. (2008)
6	2.5023	Zhao et al. (2006)
7	3.6976	Danciu and Tselentis (2007
8	3.7460	Boore and Atkinson (2008)
9	4.6455	Kalkan and Gülkan (2004)
10	5.6506	Massa et al. (2008)

Table 30. Ranking of GMPEs for PSA at T=0.30 sec (DB1$_{(rock)}$)

Rank	LLH	Model
1	1.6417	Bindi et al. (2009)
2	1.6620	Douglas et al. (2006)
3	1.8228	Cauzzi and Faccioli (2008)
4	1.8845	Akkar and Bommer (2010)
5	2.2034	Zhao et al. (2006)
6	2.4017	Cotton et al. (2008)
7	2.9496	Danciu and Tselentis (2007)
8	3.2532	Boore and Atkinson (2008)
9	3.4657	Kalkan and Gülkan (2004)
10	5.3942	Massa et al. (2008)

Table 31. Ranking of GMPEs for PSA at T=0.50 sec (DB1$_{(rock)}$)

Rank	LLH	Model
1	1.6153	Bindi et al. (2009)
2	1.6393	Akkar and Bommer (2010)
3	1.7910	Douglas et al. (2006)
4	1.8910	Cauzzi and Faccioli (2008)
5	2.3182	Cotton et al. (2008)
6	2.3962	Zhao et al. (2006)
7	3.4439	Boore and Atkinson (2008)
8	4.1488	Danciu and Tselentis (2007)
9	4.7574	Kalkan and Gülkan (2004)
10	6.7094	Massa et al. (2008)

Table 32. Ranking of GMPEs for PSA at T=1.00 sec (DB1$_{(rock)}$)

Rank	LLH	Model
1	1.6853	Bindi et al. (2009)
2	1.9355	Akkar and Bommer (2010)
3	2.0078	Cotton et al. (2008)
4	2.0112	Douglas et al. (2006)
5	2.1478	Cauzzi and Faccioli (2008)
6	2.6135	Zhao et al. (2006)
7	3.8211	Boore and Atkinson (2008)
8	4.6167	Danciu and Tselentis (2007)
9	5.0069	Kalkan and Gülkan (2004)
10	7.0880	Massa et al. (2008)

Table 33. Ranking of GMPEs for PSA at T=2.00 sec (DB1$_{(rock)}$)

Rank	LLH	Model
1	1.6820	Bindi et al. (2009)
2	2.3850	Cotton et al. (2008)
3	2.5192	Douglas et al. (2006)
4	2.5681	Akkar and Bommer (2010)
5	2.8787	Zhao et al. (2006)
6	2.9091	Cauzzi and Faccioli (2008)
7	4.2313	Boore and Atkinson (2008)
8	5.5786	Kalkan and Gülkan (2004)
9	7.9554	Massa et al. (2008)
10	8.3167	Danciu and Tselentis (2007)

D. DB2$_{(rock)}$ database:

Table 34. Ranking of GMPEs for peak ground acceleration (DB2$_{(rock)}$)

Rank	LLH	Model
1	1.2478	Boore and Atkinson (2008)
2	1.2582	Akkar and Bommer (2010)
3	1.3379	Danciu and Tselentis (2007)
4	1.3836	Kalkan and Gülkan (2004)
5	1.4803	Cauzzi and Faccioli (2008)
6	1.4976	Zhao et al. (2006)
7	1.5000	Douglas et al. (2006)
8	1.5933	Bindi et al. (2009)
9	2.0100	Massa et al. (2008)

Table 35. Ranking of GMPEs for PSA at T=0.1 sec (DB2$_{(rock)}$)

Rank	LLH	Model
1	1.4148	Boore and Atkinson (2008)
2	1.4518	Akkar and Bommer (2010)
3	1.4584	Douglas et al. (2006)
4	1.4810	Cauzzi and Faccioli (2008)
5	1.5122	Danciu and Tselentis (2007)
6	1.6363	Bindi et al. (2009)
7	1.8126	Kalkan and Gülkan (2004)
8	1.8436	Zhao et al. (2006)
9	2.1181	Cotton et al. (2008)
10	2.6784	Massa et al. (2008)

Table 36. Ranking of GMPEs for PSA at T=0.15 sec (DB2$_{(rock)}$)

Rank	LLH	Model
1	1.3366	Boore and Atkinson (2008)
2	1.4319	Danciu and Tselentis (2007)
3	1.4874	Akkar and Bommer (2010)
4	1.5783	Cauzzi and Faccioli (2008)
5	1.6105	Zhao et al. (2006)
6	1.6206	Kalkan and Gülkan (2004)
7	1.7050	Bindi et al. (2009)
8	1.7649	Douglas et al. (2006)
9	1.8391	Cotton et al. (2008)
10	2.8650	Massa et al. (2008)

Table 37. Ranking of GMPEs for PSA at T=0.20 sec (DB2$_{(rock)}$)

Rank	LLH	Model
1	1.3314	Boore and Atkinson (2008)
2	1.4641	Akkar and Bommer (2010)
3	1.4919	Zhao et al. (2006)
4	1.5040	Danciu and Tselentis (2007)
5	1.5217	Cotton et al. (2008)
6	1.5962	Kalkan and Gülkan (2004)
7	1.7347	Bindi et al. (2009)
8	1.8216	Cauzzi and Faccioli (2008)
9	1.9610	Douglas et al. (2006)
10	3.0260	Massa et al. (2008)

Table 38. Ranking of GMPEs for PSA at T=0.30 sec (DB2$_{(rock)}$)

Rank	LLH	Model
1	1.2334	Boore and Atkinson (2008)
2	1.3126	Akkar and Bommer (2010)
3	1.3891	Zhao et al. (2006)
4	1.4290	Kalkan and Gülkan (2004)
5	1.4695	Cotton et al. (2008)
6	1.6080	Danciu and Tselentis (2007)
7	1.7066	Bindi et al. (2009)
8	1.8846	Cauzzi and Faccioli (2008)
9	2.0137	Douglas et al. (2006)
10	2.7581	Massa et al. (2008)

Table 39. Ranking of GMPEs for PSA at T=0.50 sec (DB2$_{(rock)}$)

Rank	LLH	Model
1	1.3850	Akkar and Bommer (2010)
2	1.4394	Zhao et al. (2006)
3	1.4747	Boore and Atkinson (2008)
4	1.5674	Kalkan and Gülkan (2004)
5	1.7019	Cotton et al. (2008)
6	1.7146	Bindi et al. (2009)
7	2.0167	Cauzzi and Faccioli (2008)
8	2.0240	Douglas et al. (2006)
9	2.0796	Danciu and Tselentis (2007)
10	3.2977	Massa et al. (2008)

Table 40. Ranking of GMPEs for PSA at T=1.00 sec (DB2$_{(rock)}$)

Rank	LLH	Model
1	1.4902	Zhao et al. (2006)
2	1.5484	Akkar and Bommer (2010)
3	1.6763	Kalkan and Gülkan (2004)
4	1.6951	Boore and Atkinson (2008)
5	1.7400	Bindi et al. (2009)
6	1.7968	Danciu and Tselentis (2007)
7	1.8792	Douglas et al. (2006)
8	1.9188	Cotton et al. (2008)
9	1.9827	Cauzzi and Faccioli (2008)
10	3.4273	Massa et al. (2008)

Table 41. Ranking of GMPEs for PSA at T=2.00 sec (DB2$_{(rock)}$)

Rank	LLH	Model
1	1.5115	Danciu and Tselentis (2007)
2	1.5285	Akkar and Bommer (2010)
3	1.5430	Zhao et al. (2006)
4	1.6074	Bindi et al. (2009)
5	1.6086	Douglas et al. (2006)
6	1.6207	Kalkan and Gülkan (2004)
7	1.7330	Boore and Atkinson (2008)
8	1.7400	Cauzzi and Faccioli (2008)
9	2.2401	Cotton et al. (2008)
10	4.0961	Massa et al. (2008)

E. DB1$_M$ database:

Table 42. Ranking of GMPEs for peak ground acceleration (DB1$_M$)

Rank	LLH	Model
1	1.5545	Boore and Atkinson (2008)
2	1.6823	Zhao et al. (2006)
3	1.7560	Cauzzi and Faccioli (2008)
4	2.1097	Danciu and Tselentis (2007)
5	2.1482	Akkar and Bommer (2010)
6	2.1853	Bindi et al. (2009)
7	2.2154	Kalkan and Gülkan (2004)
8	2.8379	Douglas et al. (2006)
9	3.6301	Massa et al. (2008)

Table 43. Ranking of GMPEs for PSA at T=0.1 sec (DB1$_M$)

Rank	LLH	Model
1	1.5678	Boore and Atkinson (2008)1
2	1.8841	Cauzzi and Faccioli (2008)
3	1.8952	Zhao et al. (2006)
4	2.3417	Danciu and Tselentis (2007)
5	2.3879	Douglas et al. (2006)
6	2.4772	Bindi et al. (2009)
7	2.5111	Akkar and Bommer (2010)
8	2.7053	Kalkan and Gülkan (2004)
9	2.7876	Cotton et al. (2008)
10	3.1397	Massa et al. (2008)

Table 44. Ranking of GMPEs for PSA at T=0.15 sec (DB1$_M$)

Rank	LLH	Model
1	1.7053	Boore and Atkinson (2008)
2	2.0068	Zhao et al. (2006)
3	2.0812	Cauzzi and Faccioli (2008)
4	2.3458	Danciu and Tselentis (2007)
5	2.4122	Cotton et al. (2008)
6	2.6697	Douglas et al. (2006)
7	2.6931	Bindi et al. (2009)
8	2.7316	Kalkan and Gülkan (2004)
9	2.8211	Akkar and Bommer (2010)
10	3.6068	Massa et al. (2008)

Table 45. Ranking of GMPEs for PSA at T=0.20 sec ($DB1_M$)

Rank	LLH	Model
1	1.7800	Boore and Atkinson (2008)
2	1.9947	Zhao et al. (2006)
3	2.1765	Cauzzi and Faccioli (2008)
4	2.2295	Cotton et al. (2008)
5	2.6338	Kalkan and Gülkan (2004)
6	2.6851	Douglas et al. (2006)
7	2.8684	Akkar and Bommer (2010)
8	2.9038	Danciu and Tselentis (2007)
9	2.9561	Bindi et al. (2009)
10	3.7972	Massa et al. (2008)

Table 46. Ranking of GMPEs for PSA at T=0.30 sec ($DB1_M$)

Rank	LLH	Model
1	1.7770	Boore and Atkinson (2008)
2	1.9219	Zhao et al. (2006)
3	2.0818	Cotton et al. (2008)
4	2.1588	Cauzzi and Faccioli (2008)
5	2.5221	Kalkan and Gülkan (2004)
6	2.6261	Bindi et al. (2009)
7	2.6438	Akkar and Bommer (2010)
8	2.7888	Douglas et al. (2006)
9	2.9468	Danciu and Tselentis (2007)
10	3.4192	Massa et al. (2008)

Table 47. Ranking of GMPEs for PSA at T=0.50 sec ($DB1_M$)

Rank	LLH	Model
1	1.8755	Zhao et al. (2006)
2	1.9228	Boore and Atkinson (2008)
3	1.9348	Cauzzi and Faccioli (2008)
4	2.1246	Cotton et al. (2008)
5	2.1570	Akkar and Bommer (2010)
6	2.3226	Bindi et al. (2009)
7	2.4075	Kalkan and Gülkan (2004)
8	3.0870	Douglas et al. (2006)
9	4.0104	Danciu and Tselentis (2007)
10	4.9892	Massa et al. (2008)

Table 48. Ranking of GMPEs for PSA at T=1.00 sec ($DB1_M$)

Rank	LLH	Model
1	1.6751	Boore and Atkinson (2008)
2	1.6972	Zhao et al. (2006)
3	1.8126	Cauzzi and Faccioli (2008)
4	1.8581	Akkar and Bommer (2010)
5	1.8846	Kalkan and Gülkan (2004)
6	2.0106	Bindi et al. (2009)
7	2.0807	Cotton et al. (2008)
8	2.6853	Danciu and Tselentis (2007)
9	2.8758	Douglas et al. (2006)
10	4.2438	Massa et al. (2008)

Table 49. Ranking of GMPEs for PSA at T=2.00 sec ($DB1_M$).

Rank	LLH	Model
1	1.9209	Kalkan and Gülkan (2004)
2	1.9815	Akkar and Bommer (2010)
3	1.9905	Zhao et al. (2006)
4	2.1174	Boore and Atkinson (2008)
5	2.1554	Cauzzi and Faccioli (2008)
6	2.2688	Cotton et al. (2008)
7	2.4134	Douglas et al. (2006)
8	2.5840	Danciu and Tselentis (2007)
9	2.9429	Bindi et al. (2009)
10	4.3512	Massa et al. (2008)

F. DB2$_M$ database:

Table 50. Ranking of GMPEs for peak ground acceleration (DB2$_M$)

Rank	LLH	Model
1	1.3189	Akkar and Bommer (2010)
2	1.3739	Danciu and Tselentis (2007)
3	1.4081	Boore and Atkinson (2008)
4	1.4906	Bindi et al. (2009)
5	1.6775	Cauzzi and Faccioli (2008)
6	1.9034	Zhao et al. (2006)
7	2.2154	Massa et al. (2008)
8	2.4839	Douglas et al. (2006)
9	3.4098	Massa et al. (2008)

Table 51. Ranking of GMPEs for PSA at T=0.1 sec (DB2$_M$)

Rank	LLH	Model
1	1.4832	Danciu and Tselentis (2007)
2	1.5584	Akkar and Bommer (2010)
3	1.5723	Boore and Atkinson (2008)
4	1.6346	Bindi et al. (2009)
5	1.8888	Cauzzi and Faccioli (2008)
6	2.1136	Douglas et al. (2006)
7	2.2342	Zhao et al. (2006)
8	2.5033	Cotton et al. (2008)
9	2.7053	Kalkan and Gülkan (2004)
10	2.9220	Massa et al. (2008)

Table 52. Ranking of GMPEs for PSA at T=0.15 sec (DB2$_M$)

Rank	LLH	Model
1	1.4938	Danciu and Tselentis (2007)
2	1.5959	Akkar and Bommer (2010)
3	1.6148	Boore and Atkinson (2008)
4	1.6426	Bindi et al. (2009)
5	1.9098	Cauzzi and Faccioli (2008)
6	2.0581	Cotton et al. (2008)
7	2.2880	Zhao et al. (2006)
8	2.5375	Douglas et al. (2006)
9	2.7316	Kalkan and Gülkan (2004)
10	3.2661	Massa et al. (2008)

Table 53. Ranking of GMPEs for PSA at T=0.20 sec (DB2$_M$)

Rank	LLH	Model
1	1.4442	Boore and Atkinson (2008)
2	1.5954	Akkar and Bommer (2010)
3	1.6690	Cotton et al. (2008)
4	1.6746	Bindi et al. (2009)
5	1.6845	Danciu and Tselentis (2007)
6	1.8832	Cauzzi and Faccioli (2008)
7	2.2534	Zhao et al. (2006)
8	2.6338	Kalkan and Gülkan (2004)
9	2.7997	Douglas et al. (2006)
10	3.3237	Massa et al. (2008)

Table 54. Ranking of GMPEs for PSA at T=0.30 sec (DB2$_M$)

Rank	LLH	Model
1	1.3361	Boore and Atkinson (2008)
2	1.4617	Akkar and Bommer (2010)
3	1.4883	Cotton et al. (2008)
4	1.6091	Bindi et al. (2009)
5	1.7557	Cauzzi and Faccioli (2008)
6	1.8729	Danciu and Tselentis (2007)
7	2.0693	Zhao et al. (2006)
8	2.5221	Kalkan and Gülkan (2004)
9	2.8163	Massa et al. (2008)
10	3.1154	Douglas et al. (2006)

Table 55. Ranking of GMPEs for PSA at T=0.50 sec (DB2$_M$)

Rank	LLH	Model
1	1.2808	Boore and Atkinson (2008)
2	1.4034	Akkar and Bommer (2010)
3	1.5539	Cotton et al. (2008)
4	1.6251	Bindi et al. (2009)
5	1.6659	Cauzzi and Faccioli (2008)
6	1.8571	Zhao et al. (2006)
7	2.4075	Kalkan and Gülkan (2004)
8	2.4982	Danciu and Tselentis (2007)
9	3.1497	Douglas et al. (2006)
10	3.6773	Massa et al. (2008)

Table 56. Ranking of GMPEs for PSA at T=1.00 sec (DB2$_M$)

Rank	LLH	Model
1	1.3007	Boore and Atkinson (2008)
2	1.3849	Akkar and Bommer (2010)
3	1.6161	Zhao et al. (2006)
4	1.6346	Bindi et al. (2009)
5	1.6552	Cauzzi and Faccioli (2008)
6	1.8818	Cotton et al. (2008)
7	1.8846	Kalkan and Gülkan (2004)
8	1.8964	Danciu and Tselentis (2007)
9	2.7779	Douglas et al. (2006)
10	3.4162	Massa et al. (2008)

Table 57. Ranking of GMPEs for PSA at T=2.00 sec ($DB2_M$)

Rank	LLH	Model
1	1.3512	Boore and Atkinson (2008)
2	1.4995	Akkar and Bommer (2010)
3	1.7046	Cauzzi and Faccioli (2008)
4	1.7243	Bindi et al. (2009)
5	1.7296	Danciu and Tselentis (2007)
6	1.7403	Zhao et al. (2006)
7	1.9209	Kalkan and Gülkan (2004)
8	2.1456	Cotton et al. (2008)
9	2.3955	Douglas et al. (2006)
10	3.3264	Massa et al. (2008)

G. DB2$_{NF}$ database:

Table 58. Ranking of GMPEs for peak ground acceleration (DB2$_{NF}$)

Rank	LLH	Model
1	1.1580	Boore and Atkinson (2008)
2	1.1753	Akkar and Bommer (2010)
3	1.2759	Kalkan and Gülkan (2004)
4	1.3110	Danciu and Tselentis (2007)
5	1.3599	Douglas et al. (2006)
6	1.5634	Bindi et al. (2009)
7	1.8138	Cauzzi and Faccioli (2008)
8	1.9909	Zhao et al. (2006)
9	4.9263	Massa et al. (2008)

Table 59. Ranking of GMPEs for PSA at T=0.1 sec (DB2$_{NF}$)

Rank	LLH	Model
1	1.4039	Akkar and Bommer (2010)
2	1.4685	Boore and Atkinson (2008)
3	1.5087	Danciu and Tselentis (2007)
4	1.5137	Douglas et al. (2006)
5	1.5446	Kalkan and Gülkan (2004)
6	1.5502	Bindi et al. (2009)
7	2.1582	Zhao et al. (2006)
8	2.1638	Cauzzi and Faccioli (2008)
9	2.4409	Cotton et al. (2008)
10	4.1555	Massa et al. (2008)

Table 60. Ranking of GMPEs for PSA at T=0.15 sec (DB2$_{NF}$)

Rank	LLH	Model
1	1.4351	Akkar and Bommer (2010)
2	1.4656	Boore and Atkinson (2008)
3	1.4660	Danciu and Tselentis (2007)
4	1.5524	Kalkan and Gülkan (2004)
5	1.5567	Bindi et al. (2009)
6	1.6686	Douglas et al. (2006)
7	2.0242	Cauzzi and Faccioli (2008)
8	2.1036	Cotton et al. (2008)
9	2.2485	Zhao et al. (2006)
10	4.3446	Massa et al. (2008)

Table 61. Ranking of GMPEs for PSA at T=0.20 sec ($DB2_{NF}$)

Rank	LLH	Model
1	1.3359	Boore and Atkinson (2008)
2	1.4586	Akkar and Bommer (2010)
3	1.5283	Danciu and Tselentis (2007)
4	1.5747	Bindi et al. (2009)
5	1.5788	Kalkan and Gülkan (2004)
6	1.7369	Cotton et al. (2008)
7	1.7752	Douglas et al. (2006)
8	1.8872	Cauzzi and Faccioli (2008)
9	2.2556	Zhao et al. (2006)
10	4.1617	Massa et al. (2008)

Table 62. Ranking of GMPEs for PSA at T=0.30 sec ($DB2_{NF}$)

Rank	LLH	Model
1	1.2169	Boore and Atkinson (2008)
2	1.3595	Akkar and Bommer (2010)
3	1.4113	Kalkan and Gülkan (2004)
4	1.4890	Cotton et al. (2008)
5	1.6525	Bindi et al. (2009)
6	1.6891	Danciu and Tselentis (2007)
7	1.6916	Cauzzi and Faccioli (2008)
8	1.8507	Douglas et al. (2006)
9	2.1416	Zhao et al. (2006)
10	3.1890	Massa et al. (2008)

Table 63. Ranking of GMPEs for PSA at T=0.50 sec ($DB2_{NF}$)

Rank	LLH	Model
1	1.1478	Boore and Atkinson (2008)
2	1.2669	Cotton et al. (2008)
3	1.3267	Akkar and Bommer (2010)
4	1.4077	Kalkan and Gülkan (2004)
5	1.6199	Cauzzi and Faccioli (2008)
6	1.7738	Bindi et al. (2009)
7	1.8369	Zhao et al. (2006)
8	1.9961	Danciu and Tselentis (2007)
9	2.0159	Douglas et al. (2006)
10	3.5066	Massa et al. (2008)

Table 64. Ranking of GMPEs for PSA at T=1.00 sec (DB2$_{NF}$)

Rank	LLH	Model
1	1.1531	Boore and Atkinson (2008)
2	1.2490	Akkar and Bommer (2010)
3	1.3822	Cotton et al. (2008)
4	1.4315	Kalkan and Gülkan (2004)
5	1.5086	Bindi et al. (2009)
6	1.5401	Cauzzi and Faccioli (2008)
7	1.5670	Zhao et al. (2006)
8	1.6494	Danciu and Tselentis (2007)
9	1.7807	Douglas et al. (2006)
10	3.5737	Massa et al. (2008)

Table 65. Ranking of GMPEs for PSA at T=2.00 sec (DB2$_{NF}$)

Rank	LLH	Model
1	1.2073	Boore and Atkinson (2008)
2	1.3097	Akkar and Bommer (2010)
3	1.4580	Kalkan and Gülkan (2004)
4	1.4773	Cotton et al. (2008)
5	1.5910	Cauzzi and Faccioli (2008)
6	1.5917	Zhao et al. (2006)
7	1.7151	Bindi et al. (2009)
8	1.7184	Douglas et al. (2006)
9	1.9575	Danciu and Tselentis (2007)
10	3.8304	Massa et al. (2008)